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TEMPERATURES AT THE 10-MB (101,000-FOOT) LEVEL

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FOREWORD

1. General: Air Weather Service Technical Report 105-108, "Temperatures at the 10-mb (101,000-foot) Level," is published for the information and guidance of all concerned.

2. Scope: This report extends the discussion of the levels above 200 mb, begun in AWS TR 105-96, to 10 mb, which is as high as present radiosondes reach with any considerable frequency and accuracy. The results provide more detailed descriptions of the fluctuations in the temperature and density fields at such heights than have been available heretofore. A preview is given of some of the problems that will arise when analysis and forecasting at 10 mb may be required.

3. Additional Copies: Supply of this report will be in accordance with AWS Letter 5-3.

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I. INTRODUCTION

As a result of the improvement of the quality of radiosonde balloons, there was in 1951 a sudden increase in the proportion of soundings reaching 15-mb and 10-mb heights. The increase was particularly noticeable in the network covering the U.S.A., Alaska and Arctic Canada.

This relative abundance of 10-mb data permitted an investigation of the thermal structure of the 100-10 mb layer and of the behavior of the temperatures at 10-mb level. The inquiry was limited to descriptive statistical and synoptic aspects without entering into the causes of the observed phenomena. The aim was to survey 31-km temperatures from the actual data rather than by indirect methods and to provide a basis for studying twenty-four hour density changes at heights from 16 to 31 km.

All diagrams used in this report are pseudo-adiabatic charts ($\underline{T}$, $p^{0.288}$) on which the divisions of height scale decrease logarithmically with increasing elevation. Whenever heights are used in the text, they are NACA standard heights and not heights computed from hydrostatic relationship.

II. SUMMARY DESCRIPTION OF 100-10 mb LAYER

NACA Standard Atmosphere, pressure-height-temperature relationships in the lower and middle stratosphere are indicated numerically in Table I.

TABLE I.

NACA Standard Atmosphere

Mb	Feet	Km	T°C
234	35,332	10.769	-55
100	53,173	16.2	-55
50	67,692	20.6	-55
25	82,204	25.0	-55
15	92,899	28.3	-55
<u>10</u>	<u>101,389</u>	<u>30.9</u>	-55
9	103,600	31.6	-55
8.421	104,987	32	-55
5.381	114,829	35	-33
2.775	131,234	40	+3.7
1.554	147,638	45	+40.3
0.928	164,042	50	+77.0

The salient features of NACA Standard Atmosphere are:

(1) Isothermal conditions from 10.769km to 32km.

(2) Increase of the temperatures from -55°C at 32km to +77°C at 50km.

Assumption (1) had been disproved already in the 1920's. Observed conditions in the 100-10mb layer are generally characterized by a steady increase of temperatures with height, in low and middle latitudes starting from the tropopause. Gutenberg [1] utilizing 61 high radiosonde from White Sands, New Mexico, found mean tropopause at 58,000 feet with corresponding mean temperature of -65°C while the 101,000-foot temperatures were:

Jan. to Mar.	Apr. to Jun.	Jul. to Sep.
-42°C	-38°C	-33°

Nazarek [2] used pressure data from V2 rockets launched in New Mexico and derived a mean temperature of -31°C for 31km. Newell [3] using four rocket flights computed 31km temperatures ranging from -29°C to -52°C. Brasefield [4, 5] utilizing twenty high radiosonde ascents made from Belmar, New Jersey, gives the following samples of observed 31km temperatures: -38°, -42°, -44°, -46°;-51°;his mean daytime temperature curve shows -44°C at 31km and -32°C at 37km.

III. ACCURACY AND SENSITIVITY OF TEMPERATURE RECORDINGS AT GREAT HEIGHTS

The question of the accuracy and sensitivity of temperature recordings at very high levels underlies any manipulation of high-level data and any conclusions therefrom.

In the U. S. Weather Bureau and U. S. Air Force radiosonde network, the majority of the temperature readings above 100-mb heights are claimed from an analysis of system errors to be accurate within ± 1.5 -2.0. An independent study of 1400 soundings reaching at least to the 30-mb level [6] seems to justify this claim; comparison of soundings for the same station in twelve-hour intervals, comparison of temperature curves for stations lying close together and systematic behavior of temperature-height curves drawn for 4° increments of latitude, all indicate that the changes between successive significant points in individual soundings at 50- and 25-mb can be trusted, on the average, to well within ± 1°C while the mean curves for 10 soundings or more should have even higher accuracy. Note that the latter considerations involve only the temperature differences from one level to another, i.e., the lapse rate. Nothing can be deduced from our data about the accuracy of absolute values of the recorded temperatures at 25-km or 30-km heights.

Figure 1 may serve as a qualitative indication of the sensitivity of radiosonde recordings at very high level. On 13 January 1951, in the layer between 100- and 15mb, eight U.S.A. stations show a number of exactly identical details in the vertical structure. On the left of Figure 1, curves No. 1, 2, 3 represent east coast stations while curve No. 4 is for Lander, Wyoming. Detail A is registered at all four stations; detail B at Nos. 2 and 3 while detail C appears at Nos. 2, 3, 4.

On the right of Figure 1, curves Nos. 5, 6, 7 are for the Mid-west stations while No. 8 is for Charleston, South Carolina. Detail A' is recorded at all four of them. It will be noticed that A' differs only quantitatively from A. Detail B' is also present in all four curves; it is not certain, however, whether B' corresponds to B or to A.

Closer study of this interesting multi-layer structure over a large geographical area has not been made and no explanation is offered. For our purpose it is sufficient to note that change of lapse rate in A' is registered by a 1°C temperature differences, while that at A involves temperature difference of 2°C and, in one case, of 3°C. It is obvious that temperature recordings over a wide area have been, in this particular case, sensitive to within 1°C.

From a great number of examples similar to that discussed on Figure 1, it can be concluded that, on the average, a high degree of confidence can be placed in the 1951 temperature records reaching the 15-and 10-mb levels.

The question arises whether the construction of 10-mb contour charts is feasible. It was found earlier [6] that analysis of 25-mb charts is very troublesome and requires correction of most 25-mb heights by the aid of 200-mb heights adjusted to smoothed 200-mb contours. Even so, recomputed 25-mb data gave consistent-looking contour patterns only when contours were drawn for 400-foot intervals. The reason for this inaccuracy of height data needs closer consideration.

The thickness of a given isobaric layer (for example such as 25-10 mb) is computed from

$$\Delta h = C \ln \frac{p_1}{p_2} T$$

where both $\underline{C}$ and $\ln (p_1/p_2)$ are constants. In computation, pressures $\underline{p_1}$ and $\underline{p_2}$ are fixed but in reality pressure carries observational and calibration errors. In the 100-to 10-mb layer, these errors can amount to 3-5 mb. How much is Δh changed if the pressure in the layer is 3mb or 5mb off?

When computing a thickness on an adiabatic chart, the distance between $\underline{p_1}$ and $\underline{p_2}$ must be chosen small or else the estimate of the mean temperature will be

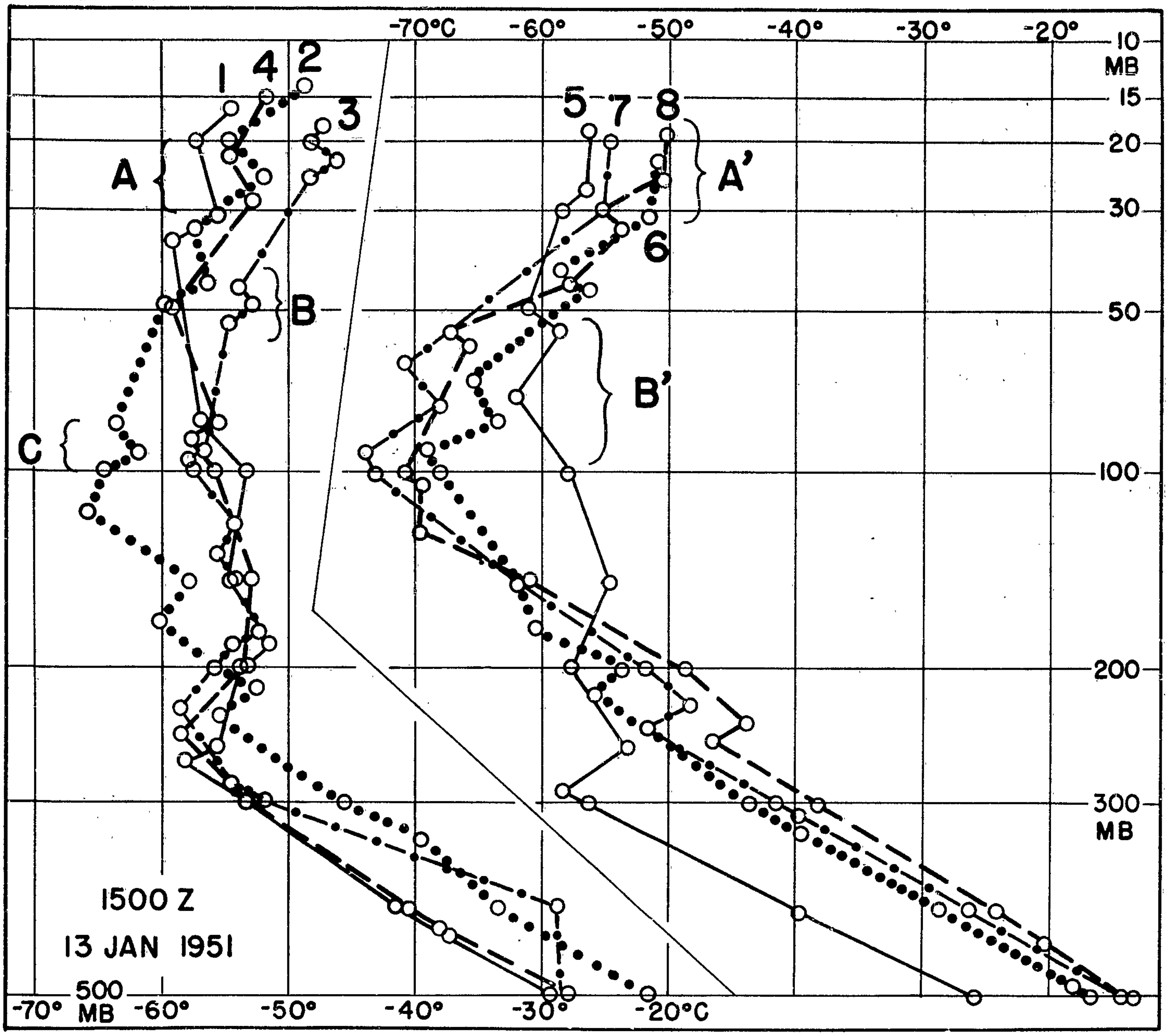


FIG.1. HIGH SOUNDINGS FOR 13TH JANUARY 1951, 1500 Z, SHOWING THE SAME DETAILS A, B, C, A', B'.
CURVE NO. 1 = PORTLAND, MAINE
CURVE NO. 2 = WASHINGTON, D.C.
CURVE NO. 3 = ROME, N.Y.
CURVE NO. 4 = LANDER, WYO.
CURVE NO. 5 = OMAHA, NEB.
CURVE NO. 6 = LITTLE ROCK, ARK.
CURVE NO. 7 = LAKE CHARLES, LA.
CURVE NO. 8 = CHARLESTON, S.C.

inaccurate. For example, if the 100-10 mb mean temperature is estimated in one step, evaluation error of $\pm$ 2°C in $\overline{T}$ would be very likely and it would result in $\pm$ 440-foot error in thickness.

In the 356 soundings examined for this report the extreme temperature difference between 25 mb and 10 mb was 23°C. If in this extreme case the pressures in the 25-10 mb layer are erroneous and are 3 mb too low, we have:

Correct thickness of 25-10 mb layer = 22,160 feet

25-10 mb thickness with −3 mb error in $\underline{p}$ = 21,760 feet

Error in thickness = −400 feet

If the error in $\underline{p}$ is +4 mb or +5 mb, the errors in thickness are 530 feet and 670 feet respectively. Even if the temperature difference between 25 mb and 10 mb is only 7°C, i.e., close to the all-year normal, the thickness error for 3-mb pressure error will be about 130 feet.

On these grounds it seems that it would be futile to attempt construction of 10-mb daily contour maps, at least until observational accuracy is improved.

A more detailed discussion of the errors of the radiosonde and their effects on the reported values of heights at high levels will be found in an Appendix to this Report.

IV. STATISTICS ON SOUNDINGS USED

Utilized in the present investigation were 356 soundings reaching at least 15 mb. In 96 cases, the soundings actually reached 10-mb level. In the remaining 260 cases, termination point was between 11 mb and 15 mb.

From the latter soundings, 10-mb temperatures were obtained by extrapolating linearly through a deep layer from well below the termination point. Cases in which the lapse rate changed rapidly just below termination point were not included.

The material represented U.S.A., Alaskan, Canadian and Caribbean stations, including Atlantic and Pacific ships close to the American continent. The data was from four mid-seasonal months of 1951, namely from January, April, July and October 1951.

For each month the data was divided into four main groups according to zones of geographical latitude. In Table 2, these groups are numbered I, II, III, IV. Additional groups No. V and No. VI were also used for July and January respectively.

TABLE 2.

Number of Soundings Reaching 10 mb

Group No.	I	II	III	IV	V	VI	Without Group	Total Number of Cases
Latitude Zone:	9°–33°	35°,36°	38°–48°	53°–65°	76°–79°	53°		
1951:								
January	17	10	28	—	—	5	2	62
April	12	10	54	31	—	2	2	91
July	14	10	21	33	11	5	2	96
October	23	17	49	15	—	—	3	107

There is no Group IV in January, owing to the usual failure of the balloons to reach great heights in winter-time in high latitudes.

Regarding the four main groups, Table 2 shows that the greatest confidence should be placed in the values of Groups III and IV, and least confidence in Group II. Group VI stands on its own and contains twelve exceptionally warm soundings from station 414 (53°N, 174°E) on the Aleutian Chain.

The 10-mb mean temperatures for all groups are given in Table 3. The value of -86.5°C for Alert (82°N, 62°W) is an extrapolation of 14 cases of which only 9 reached 60-mb level.

TABLE 3.

Seasonal 10-mb Mean Temperatures (in °C)

Group:	I	II	III	IV	V	VI
January	-45.1	-50.0	-48.2	—	(-86.5)	-38.7
April	-38.8	-45.4	-48.6	-52.6	—	—
July	-38.0	-42.8	-39.3	-37.3	-38.1	(-12.7)
October	-43.5	-46.6	-48.6	-47.1	—	—

Table 4 gives 10-mb maximum temperatures encountered in each group, while Table 5 shows 10-mb minima.

TABLE 4.

10-mb Maximum Temperatures Encountered (in °C)

Group	I	II	III	IV	V	VI
January	-37.5	-44.0	-39.0	—	—	-31.2
April	-29.5	-38.8	-10.0	-34.2	—	(-19.8)
July	-25.5	-26.0	-23.0	-28.0	-35.5	(-5.0)
October	-36.5	-39.0	-36.0	-36.3	—	—

TABLE 5.

10-mb Minimum Temperatures Encountered (in °C)

Group	I	II	III	IV	V	VI
January	-55.0	-57.0	-62.0	—	—	-44.0
April	-46.2	-55.7	-60.5	-63.0	—	—
July	-45.0	-59.0	-46.5	-50.0	-44.4	(-22.0)
October	-51.6	-57.0	-56.5	-54.0	—	—

Table 3 shows that 10-mb mean temperatures display a marked annual variation, which amounts to 7.1°C in Group 1, 7.2°C in Group II and 9.3° in Group III. The yearly maximum occurs in July, the minimum in January. For Group IV, January values are not available, but the difference between April and July is already 15.3°. In Group V, the difference between January and July temperatures is 48.4°C.

V. THERMAL STRUCTURE OF THE 100-10 mb LAYER

For all 356 soundings, temperatures for 100-, 50-, 25-, 15- and 10-mb were tabulated separately for each Group and each mid-seasonal month. Figure 2 shows the mean soundings schematically reconstructed in this way, with the Group number near each curve.

It is seen that latitudinal variation of 10-mb temperature is generally

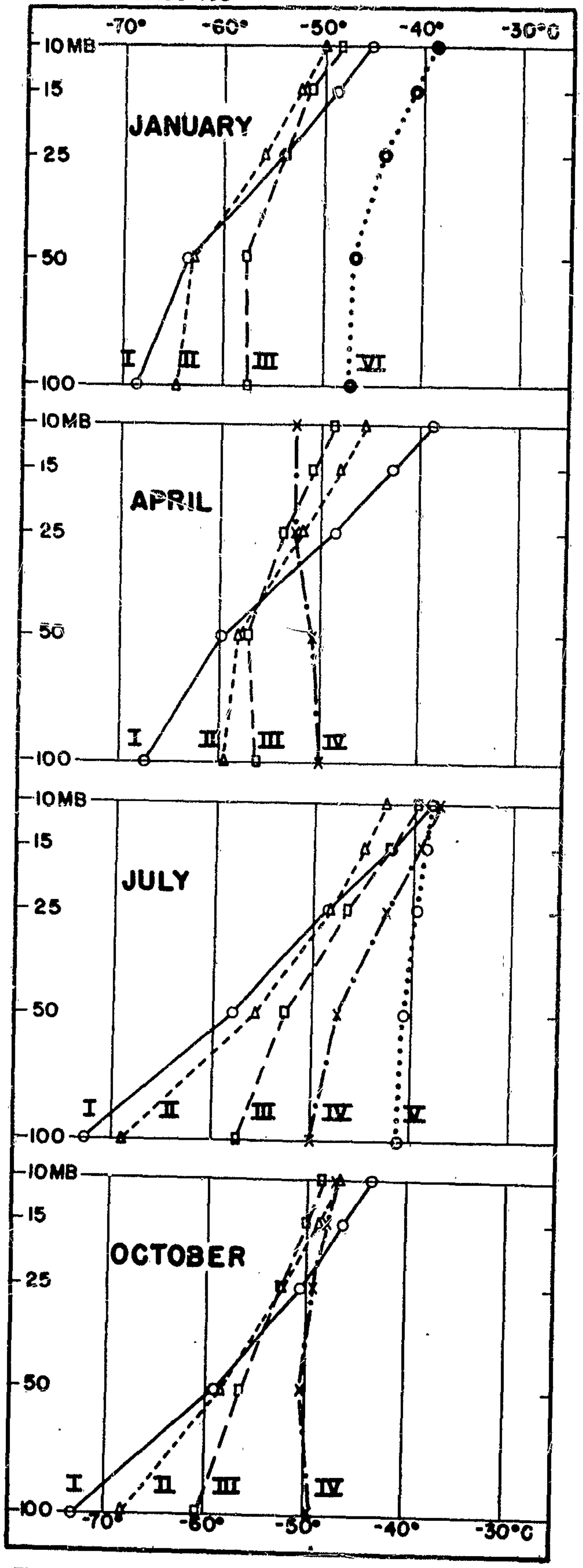


FIG. 2. MEAN-100-10 MB TEMPERATURE CURVES FOR LATITUDE GROUPS GIVEN IN TABLE 2.

smaller or much smaller (July and October) than the variation of 100-mb temperature. Convergence of the curves in higher altitudes is noticeable in all four months and it is particularly regular in July and October. In April, mutual intersection of all curves in the region between 40-mb and 20-mb marks a barotropic layer.

In all months there is a tendency for the low-latitude curve (Group I) to be warmer at 10-mb than curves No. II,III, IV and even V. Thus the 10-mb temperatures in 9^{o}-33^{o}N latitude seem to be, on the average, higher than those in 35^{o}-79^{o}N region.

Curves of Figure 2 represent vertical structure only schematically, each curve being based on merely five points. A far more detailed picture can be obtained by averaging temperatures for small pressure intervals. Figure 3 illustrates mean curves for September 1951 for four U. S. A. stations arranged according to the increasing geographical latitude. The range of latitude is from 28^{o}N for A to 48^{o}N for D. The maximum spread of temperature (17^{o}C) occurs at 100-mb. At 40-mb all curves converge and are practically the same up to 15-mb, marking a deep barotropic layer. The spread at 15 mb is only 2.5^{o}C. At 15 mb, curve A (28^{o}N) is again slightly warmer than the other three curves. The average distribution of temperature in 100 mb -5 mb layer can be summarized by the following statistics:

(a) All-year mean temperatures for 329 stations located between 9^{o}N and 65^{o}N:

At:	100 mb	50 mb	25 mb	15 mb	10 mb	5 mb
$T^{o}C$	-60.8	-56.0	-50.4	-46.9	-44.4	-36.6

(b) All-year mean temperatures for 179 stations located between 35^{o}N and 48^{o}N:

At:	100 mb	50 mb	25 mb	15 mb	10 mb	5 mb
$T^{o}C$	-61.8	-57.5	-51.9	-48.6	-46.2	-36.3

In both tabulations, the mean temperature for 5-mb level is based on 23 soundings distributed between 32^{o}N and 61^{o}N.

VI. THE MEAN LAPSE-RATE

Table 6 gives mean vertical lapse rates for the following layers: 100-50, 50-25, 25-15, 15-10 mb. Heights in the NACA Standard Atmosphere were assigned to these pressures, the 100-50 mb layer corresponding to the 16.2-20.6km layer, and so on.

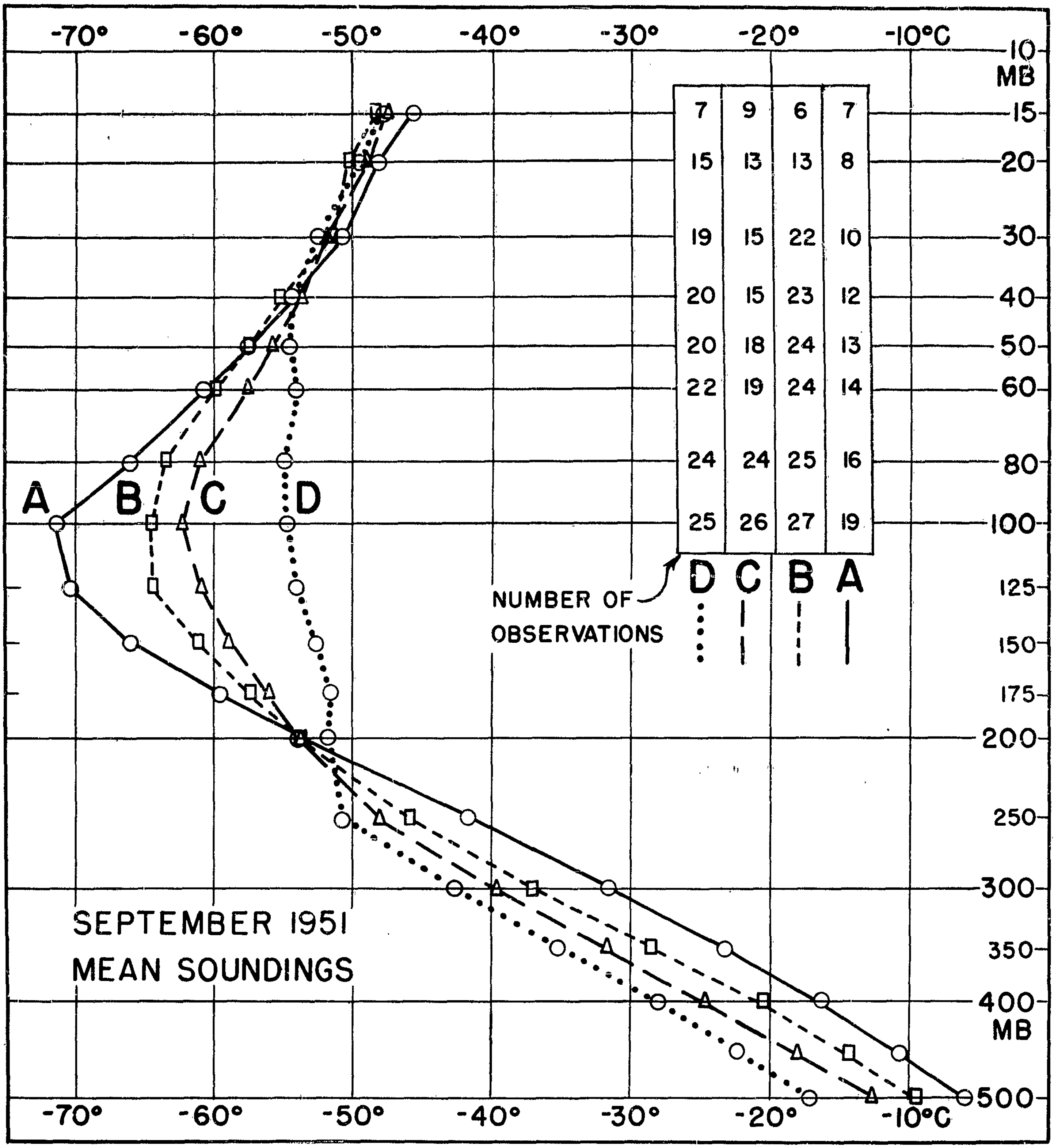


FIG. 3. MEAN SOUNDINGS FOR SEPTEMBER 1951
A= TAMPA, FLA. (28°N)
B= ELY, NEV. (39°N)
C= NORTH PLATTE, NEBR. (41°N)
D= GLASGOW, MONT. (48°N)

TABLE 6.

Mean vertical lapse rate in°C per kilometer (positive values indicate warming with height, values with asterisks refer to cooling with height)

(J, A, J, O = January, April, July, October)

	Group Number											
	I				II				III			
Layer: (km)	J	A	J	O	J	A	J	O	J	A	J	O
16.2-20.6	1.2	1.8	3.4	3.2	0.4	0.3	3.0	2.3	0.1*	0.2*	1.1	0.9
20.6-25.0	2.2	2.5	2.1	1.9	1.6	1.5	1.7	1.5	0.9	0.8	1.4	1.0
25.0-28.3	1.5	1.7	2.1	1.3	1.1	1.2	1.1	1.0	0.7	0.8	1.4	0.7
28.3-30.9	1.5	1.6	1.6	1.1	0.9	1.0	0.8	0.9	1.3	0.8	1.1	0.5

	IV				V				VI			
Layer: (km)	J	A	J	O	J	A	J	O	J	A	J	O
16.2-20.6	—	0.2*	0.6	0.3*	0.1	—	—	—	0.1	—	0.8	—
20.6-25.0	—	0.4*	1.1	0.2	0.3	—	—	—	0.7	—	1.6	—
25.0-28.3	—	0.0	1.0	0.4	0.3	—	—	—	0.9	—	2.5	—
28.3-30.9	—	0.0	0.8	0.4	0.3	—	—	—	0.8	—	2.5	—

It is seen that the lapse rate is far from constant and that warming with height generally decreases in the upper two layers (25-28.3 km and 28.3-30.9km). There are only seven positions with lapse rates from 2.1°to 3.0°C/1km and only two positions with values of lapse rate greater than 3.0°C/1km. Nazarek [2] gives the following mean lapse rates for New Mexico:

15-25km	20-30km	25-35km
0.9°C/1km	1.9°C/1km	2.8/1km

The values 1.9° and 2.8°/1km seem to be considerably in excess from those in Table 6.

VII. EXTREME CASES

Examination of 356 soundings showed that extremely high 10-mb temperatures are encountered at Shemys (52° 43°N, 174° 06 E) on the Aleutian chain. All examined 10-mb data for this station is given in Table 7. For comparison, the 100-mb temperatures are also tabulated.

TABLE 7.

100-mb and 10-mb Temperatures for Shemys (53°N, 174°E) -- Values in brackets are extrapolated. All dates are 1951.

Date (1951)	Time	Temp. at 100-mb	Temp. at 10-mb	Last point recorded
11 January	15Z	-45.0°	(-41.5°)	13mb, -42°
4 February	03Z	-46.0°	-31.2°	8mb, -30°
5 February	03Z	-49.0°	(-36.0°)	15mb, -38°
6 February	03Z	-50.0°	-41.0°	
8 February	03Z	-46.0°	-44.0°	
6 April	03Z	-42.6°	-21.4°	11mb, -22°
7 April	03Z	-42.7°	-19.8°	11mb, -20.4°
8 July	03Z	-40.0°	-22.0°	
9 July	03Z	-38.0°	-20.0°	6mb, -10.5°
10 July	03Z	-36.0°	(- 9.5°)	15mb, -13.5°
12 July	03Z	-39.0°	(- 5.0°)	11mb, - 6.2°
13 July	03Z	-37.5°	(- 7.0°)	15mb, -15.6°
4 October	03Z	-50.8°	(-47.0°)	15mb, -48.5°
6 October	03Z	-53.0°	(-46.6°)	2mb, -44.1°

Most of the data in Table 7 is from 0300Z i.e., approximately 3 p.m. local time for Shemys. Thus there is a possibility that the extremely high temperatures recorded in April and July are influenced by sustained insolation of the instruments. No investigation was possible to establish whether this is the case. However, fairly low 10-mb temperatures registered in February and October (when the sun is insolating the radiosonde instrument) indicate that both winter and summer values may be correct.

Figure 4 illustrates doubtful series of July 8, 9, 10, 12 and 13, for Shemya. It should be remembered that in the NACA Standard Atmosphere (see Table 1), the temperatures begin to rise from -55° at 32 km to + 3.7° at 40 km. It is possible that on some occasions the layer in which sudden increases of temperature occurs with elevation, comes down to or below the 10-mb (31km) level. This would account for extremely high 10-mb temperatures in the series of July 8-13, 1951.

It should be mentioned that Scherhag's data [7] of 142 cases of 10-mb temperatures over Berlin (from March 1951 to March 1952 period), gives absolute maximum at 10-mb as -12°C and absolute minimum of -70°C.

From 356 cases studied in this report, Group VI (i.e., Shemya was excluded and then two cases of the highest and lowest 10-mb temperatures were sought in each month. They are given in Table 8, together with temperatures for 100, 50, 25 and 15 mb.

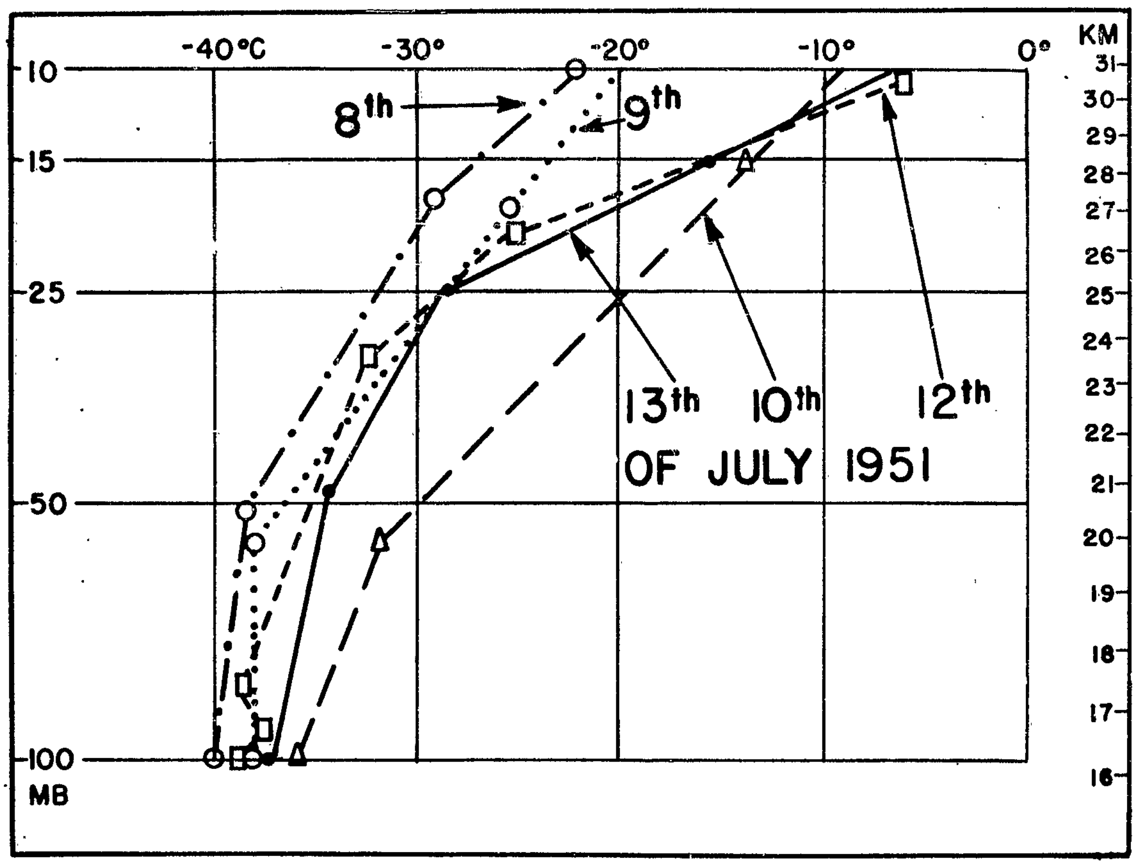


FIG. 4. DAILY SOUNDINGS FOR STATION 414 (53°N, 174°E) FOR JULY 8TH TO JULY 13TH, 1951. ALL OBSERVATIONS ARE 0300Z, I.E. 1500 LOCAL TIME. NOTE STEADY INCREASE OF 10-MB TEMPERATURES FROM 8 JULY TO 13 JULY, WHILE 100 MB TEMPERATURE REMAINS FAIRLY CONSTANT.

TABLE 8.

Extreme Temperatures (exclusive of those in Table 7).
(In Negative Degrees Centigrade.)

Date	Time	Station	Location	Temperatures at: 100	50	25	15	10mb
16 Jan.	15Z	FWH	33°N - 97°W	70	58	53	41.5	37.5
15 Jan.	15Z	RME	43°N - 75°W	55	54.5	49	44	39
9 Jan.	15Z	RME	43°N - 75°W	57.5	58	54	56	62
2 Jan	15Z	520	40°N - 80°W	66	62	61.4	60.5	60
6 Apr.	15Z	FLV	39°N - 96°W	41	39	27.6	16.7	10
2 Apr.	15Z	501	17°N - 84°W	78.5	65.5	48	37.3	30
4 Apr.	15Z	381	58°N -135°W	52.8	56.6	59.8	61.7	63
6 Apr.	15Z	082	82°N - 62°W	50.4	54.8	58.3	60.7	62.1
4 Jul.	15Z	815	48°N - 59°W	48	56.5	40	30	23
5 Jul.	15Z	270	32°N -106°W	78	57.5	42	32.5	25.5
6 Jul.	15Z	SHIP	35°N - 48°W	67	59.6	53.5	53.5	55
10 July	15Z	361	59°N -140°W	57	52.8	49	49.6	50
2 Oct.	15Z	308	37°N - 76°W	65	54.5	43.7	39	36
1 Oct.	15Z	816	53°N - 60°W	46	44	43	39.2	36.3
13 Oct.	03Z	353	35°N - 97°W	69	61.8	59.5	58.2	57
6 Oct.	15Z	405	39°N - 77°W	69.5	58.8	52	54.4	56.5

VIII. COOLING WITH HEIGHT

In the 100-10mb layer the temperature generally increases from the bottom to the top of the layer, except over the polar cap in winter, where steady cooling with elevation takes place.

However, even in the lower latitudes the temperature in the 100-10mb layer may occasionally decrease with height. Out of 356 cases examined, cooling in the vicinity of 10-mb level occurred in 45 instances.

The levels from which the curves showed cooling to 10-mb heights were as follows:

Cooling from:	Jan.	Apr.	Jul.	Oct.
100mb to 10mb	0	11	1	3
89-50mb to 10mb	0	9	0	0
49-26mb to 10mb	1	2	0	2
25mb to 10mb	4	2	4	6

The cases in which the maximum cooling occurred were as follows:

January

20 - 10mb 11.0°C
20 - 10mb 11.0°C

April

100 - 10mb 11.7°C
100 - 10mb 11.1°C
84 - 10mb 10.7°C
100 - 10mb 10.2°C

July

20 - 10mb 11°0 C

October

22 - 10mb 5°9C

Otherwise the amount of cooling was distributed evenly between 0.2°C and 9.6°C.

Stations in which cooling with height was registered, were distributed between 33°N and 82°N latitude, as shown in Table 9.

TABLE 9.

Geographical Distribution of Cases in Which Cooling with Altitude Occurred

Latitude:	33°-40°	41°-50°	51°-60°	61°-70°	71°-80°	82°
January	3	2	—	—	—	—
April	1	1	4	16	—	2
July	2	1	1	—	1	—
October	4	3	3	1	—	—

IX. THE TWENTY-FOUR HOUR TEMPERATURE CHANGES

Out of 356 cases there were 61 pairs for which 10-mb data was available for the same station in a twenty-four hour interval. On these 61 pairs, twenty-four hour changes of temperature were computed for 100, 50, 25, 15 and 10 mb.

A surprising result was obtained: changes at 10 mb were the greatest of all, and about twice as large as those at 100 mb.

Table 10 gives the frequency of 100- and 10-mb temperature changes in a twenty-four hour interval. The values are arranged in frequency classes of 2°C.

TABLE 10.

Frequency of Twenty-four Hour Temperature Changes
at 100 and 10 mb (in °C)

	Value of 24-hour temperature change:						
	0-1.9°	2-3.9°	4-5.9°	6-7.9°	8-9.9°	10-11.9°	12-13.9°
Jan. 100mb	4	3	4	0			
Jan. 10mb	4	0	4	3			
Apr. 100mb	11	7	2	0			
Apr. 10mb	7	4	2	3	3	0	1
Jul. 100mb	9	4	1	0	1		
Jul. 10mb	4	2	5	1	0	3	
Oct. 100mb	10	4	1	0			
Oct. 10mb	6	4	1	2	2		

It is evident that small changes (0°-3.9°), so frequent at 100 mb, are much less frequent at 10 mb. However, changes greater than 6°C are absent at 100 mb while they are fairly frequent at 10 mb.

Mean changes at 100, 50, 25, 15 and 10 mb and maximum changes encountered at 100 and 10 mb are given in Table 11.

TABLE 11.

(J, A, J, O = January, April, July, October)

	Average T°-24 hour J	A	J	O	Maxima T° 24-hour J	A	J	O
100mb	2.5°	1.7°	2.2°	1.8°	5.0°	4.3°	9.0°	5.0°
50mb	2.8°	1.9°	2.2°	1.4°				
25mb	2.6°	1.8°	2.9°	2.6°				
15mb	3.1°	2.6°	3.9°	2.7°				
10mb	3.9°	4.3°	4.8°	3.5°	7.0°	13.7°	11.5°	8.8°

It is seen that the mean values of the 24-hour change increase regularly with height, reaching a maximum at 10 mb in July. The extremes at 10 mb are always higher than those at 10 mb.

Scherhag [7] recorded the following twenty-four hour temperature changes:-

Over Berlin and at 25 mb: 20°C in two cases out of 22.

Over Thule and at 40mb: 13°C in one case out of 7.

In one case the 48-hour temperature rise at 10 mb was 36°C.

Values given in Tables 9 and 10 are regardless of sign, i.e., they are for both warming and cooling in twenty-four hour interval. The question arises whether there is any correlation between the sign and the value of 10- and 100-mb changes. It was found that positive changes at 10-mb occur with both positive and negative changes at 100 mb. The same applies to negative changes at 10 mb. This inconclusive result can be summarized as follows:

	Number of cases where: 100- and 10-mb changes are of the same sign	100- and 10-mb changes are of the opposite sign
January	8	3
April	9	11
July	4	11
October	8	7

X. SYNOPTIC EXAMPLE OF 10-MB TEMPERATURES

From the available material, the day with the most numerous 10-mb data was chosen for an attempt to analyze 10-mb isotherms. This was 2 July 1951, for which 21 observations were available. It is seen from Figure 5 that the data was scattered over a very wide area, from Panama (9°N) to Isachsen (79°N).

Figure 5 shows that 10-mb temperatures over this large area are very uniform indeed. The situation corresponds to the beginning of the polar summer and generally higher temperatures are observed over the Arctic. However, the highest temperature on the map appears at Las Vegas, Nevada (-29°C). The lowest temperature appears at Nashville, Tennessee (-44°C), thus the range over the map is 15°C. Panama registers -40.3°C, a slightly higher temperature than those over Eastern U. S. A. and the Atlantic.

The isotherms on Figure 5 were drawn with the aid of 100-mb isotherms. Since there is usually an increase of temperatures from 100- to 10-mb, and since low-latitude stations are usually warmer at 10 mb than stations north of 35°N, 100-mb isotherms were followed in construction of Figure 5.

Figure 6 gives 100-mb isotherms drawn to 80 stations represented by the black dots. The closed -40° isotherm in Northern Canada served as a guide for introducing a -35° isotherm on the 10-mb map (of Figure 5).

The minimum temperature on the 100-mb chart is at Panama: -75.0°C, the maximum at Coppermine (68°N): -38.6°C. Thus the absolute range is 36.4°C, i.e., two and a half times greater than that at 10 mb. However, if only those 100-mb stations are considered which reach the 10-mb level, the range is from -75.0°C (Panama) to -41.0°C (Mould Bay, 76°N), i.e., 34°C.

XI. CONTOUR AND ISOTHERM ANALYSIS AT 20 MB

It has been shown elsewhere [6] that construction of daily 25-mb synoptic maps is a feasible proposition. A new example will be discussed below, comparing 100-mb and 20-mb mean maps for September 1951.

Figure 7 illustrates 100-mb mean conditions for September 1951. The map is based on fifty U. S. A. and Caribbean stations. The isotherms are drawn for every 2°C. The lowest mean temperature is found at Ciudad Victoria (-77.0°C), the highest at International Falls (-54.5°), giving the range of 22.5°C. Contours show a pattern characteristic for summer months with a belt of high pressures in the south and a ridge over the west coast.

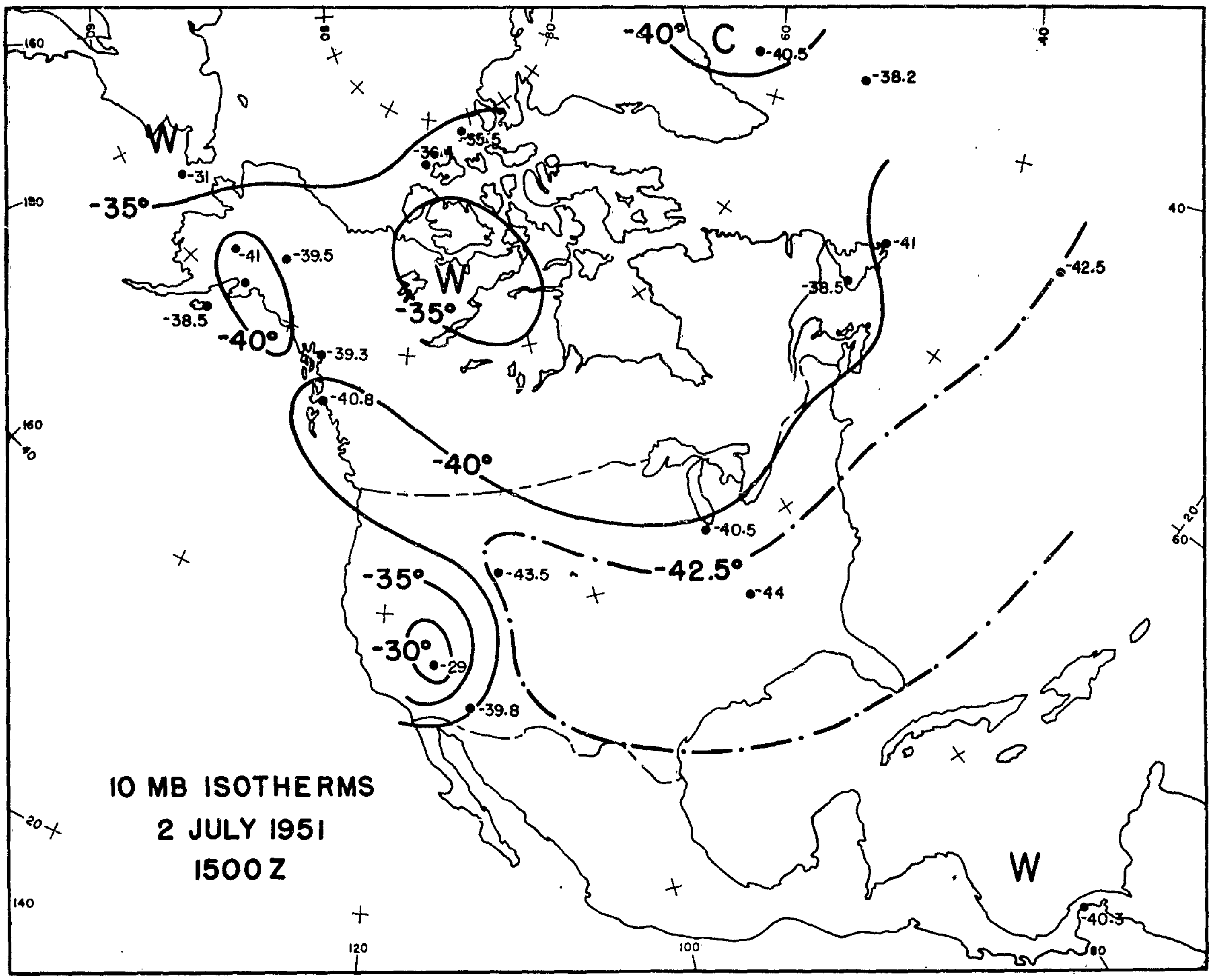

10 MB ISOTHERMS
2 JULY 1951
1500 Z
-40°
C
-40.5
-38.2
W
-31
-35°
-35.5
-36.4
W
-35°
-41
-39.5
-38.5
-40°
-39.3
-40.8
-40°
-41
-38.5
-42.5
-40.5
-42.5°
-43.5
-44
-35°
-30°
-29
-39.8
W
-40.3

FIG. 5

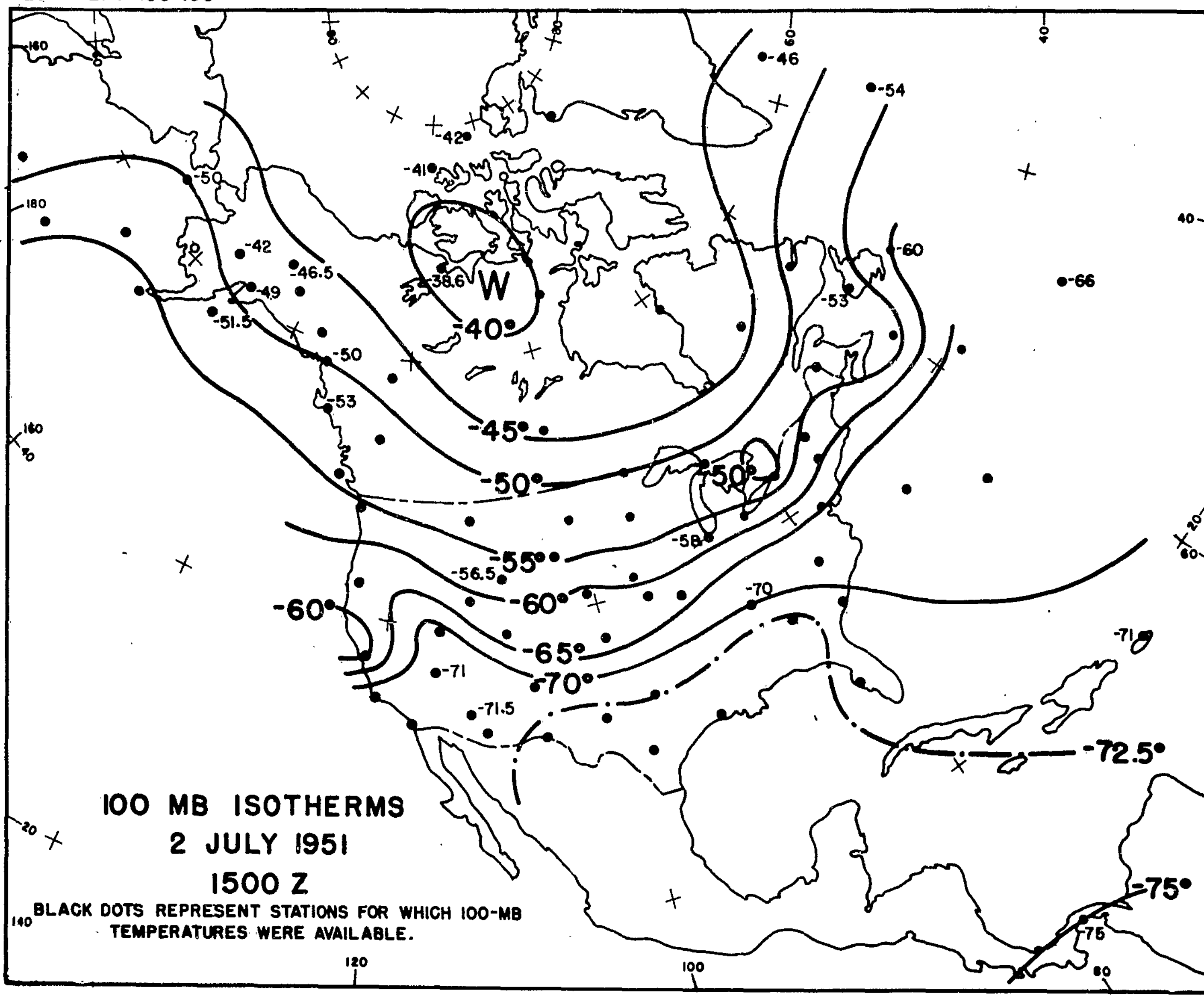

100 MB ISOTHERMS
2 JULY 1951
1500 Z
BLACK DOTS REPRESENT STATIONS FOR WHICH 100-MB TEMPERATURES WERE AVAILABLE.
W
-40°
-45°
-50°
-55°
-60°
-65°
-70°
-72.5°
-75°

FIG. 6

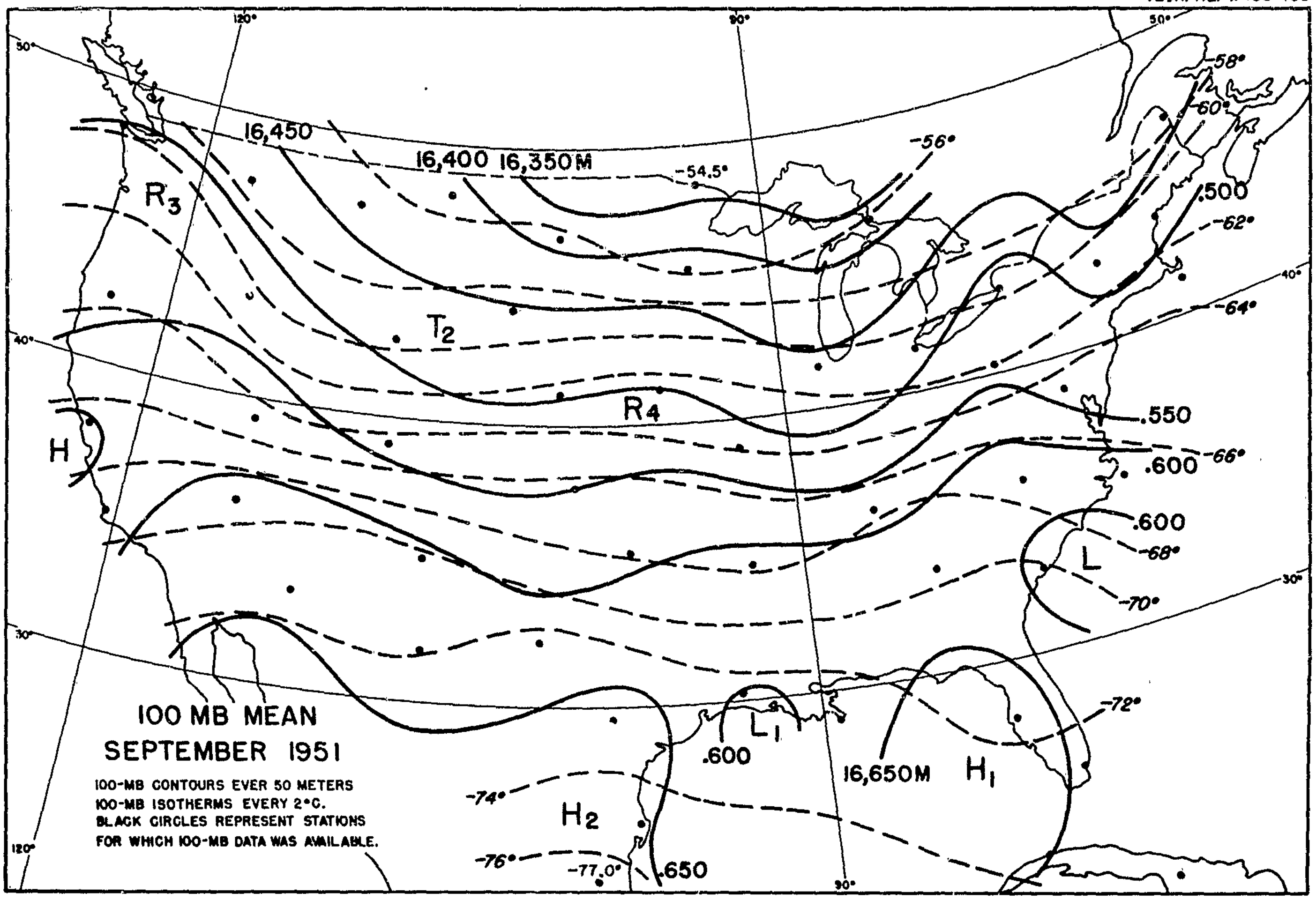

100 MB MEAN
SEPTEMBER 1951
100-MB CONTOURS EVER 50 METERS
100-MB ISOTHERMS EVERY 2°C.
BLACK CIRCLES REPRESENT STATIONS
FOR WHICH 100-MB DATA WAS AVAILABLE.
16,450
16,400
16,350M
-54.5°
-56°
-58°
-60°
.500
-62°
-64°
.550
.600
-66°
.600
-68°
-70°
-72°
-74°
-76°
-77.0°
.650
.600
16,650M
R3
T2
R4
H
L
L1
H1
H2
120°
90°
50°
40°
30°

FIG. 7

Figure 8 pictures mean 20-mb conditions for September 1951. Figures in brackets indicate the number of observations which went into the means. 20-mb isotherms on Figure 8 are drawn for every 1°C. The lowest temperature is at Atlanta, Georgia (-50.6°C), the highest at San Antonio, Texas (-47.9°C). There seems to be two belts of -50°C temperatures, one on the east coast and one on the west coast. South of these belts, the temperatures increase to -48°C. This is in agreement with previously stated fact that 10-mb temperatures in the 9 -33°N zone are higher than 10-mb temperatures in middle and high latitudes.

Very little confidence should be placed in the 20-mb contours shown by Figure 8. However, certain similarity and consistency between 100- and 20-mb contour-fields are worth mentioning. In the south, features marked H_1, L_1, and H_2 on the 20-mb map, have corresponding features on the 100-mb map. In these features, geostrophic gradient at 20 mb is, however, much stronger than at 100 mb.

In the northwest and north, the H_3 and H_4 on the 20-mb map, have corresponding ridges R_3 and R_4 at 100 mb. Similarly, L_2 at 20 mb corresponds to trough T_2 at 100 mb.

This tendency for 20-mb contours to show a broken-up pattern and to maintain, at the same time, a vertical consistency with major 100-mb contour-features, seems to be a rule at these very high levels [6].

XII. TEMPERATURES BETWEEN 32KM AND 42KM

In the examined material there were 24 soundings reporting temperatures at pressures from 8mb to 2mb. Although it is realized that radiosonde recording of the pressure at these extreme heights is very inaccurate, the soundings give some indications of the temperature behavior of levels from 32km to 42km.

Tabulated in Table 12, are the temperatures for the terminal points of these very high soundings, together with corresponding 10-mb and 100-mb temperatures. The height of the terminal point is given in the NACA Standard Atmosphere:

TABLE 12.

Date	Time	Location	Temperatures in °C at:-		
			100mb	10mb	Terminal Point
1 Jan.	15Z	32°N, 86°W	-70	-43	7mb, 33.3 km, -40
16 Jan.	15Z	43°N, 83°W	-53	-47	5mb, 35.6 km, -41.5
27 Jan.	15Z	9°N, 80°W	-76	-47	6mb, 34.3 km, -41
4 Feb.	03Z	53°N, 174°E	-46	-31.2	8mb, 32.4 km, -30

TABLE 12 (Cont'd)

1 Apr.	15Z	39°N, 96°W	-56	-45	7mb, 33.3 km, -39
2 Apr.	15Z	32°N, 111°W	-63.2	-37.2	7mb, 33.3 km, -32
3 Apr.	15Z	39°N, 96°W	-54.7	-43	8mb, 32.4 km, -40.8
4 Apr.	15Z	40°N, 105°W	-57.5	-47.8	8mb, 32.4 km, -47.5
6 Apr.	15Z	41°N, 112°W	-57	-47.4	7mb, 33.3 km, -46
8 Apr.	15Z	43°N, 83°W	-50	-39.2	8mb, 32.4 km, -36.5
8 Apr.	15Z	39°N, 96°W	-51.8	-41.5	4mb, 37.1 km, -38.8
8 Apr.	15Z	32°N, 65°W	-63.2	-34.2	7mb, 33.3 km, -29.5
12 Apr.	03Z	55°N, 163°W	-48.8	-34.2	5mb, 35.6 km, -30.5
2 July.	15Z	9°N, 80°W	-75	-40.3	7mb, 33.3 km, -39
4 July	15Z	48°N, 53°W	-52	-36.5	7mb, 33.3 km, -33
5 July	03Z	39°N, 77°W	-65	-43.2	4mb, 37.1 km, -40
5 July	15Z	35°N, 47°W	-69	-37.2	7mb, 33.3 km, -35
9 July	03Z	53°N, 174°E	-38	-20	6mb, 34.3 km, -10.5
1 Oct.	15Z	48°N, 53°W	-52	-42.9	5mb, 35.6 km, -41
2 Oct.	15Z	61°N, 45°W	-45	-47.5	5mb, 35.6 km, -48
3 Oct.	15Z	61°N, 45°W	-47.5	-46.7	5mb, 35.6 km, -45.7
5 Oct.	15Z	60°N, 112°W	-50.7	-46.8	5mb, 35.6 km, -46.7
6 Oct.	03Z	53°N, 174°E	-53	-46.6	2mb, 42.6 km, -44

It is seen that, with one exception, the temperature continues to rise above the 10-mb level. Maximum temperature encountered was -10.5°C at 5mb. The highest elevation reached was 42.6 km with the temperature of -44°C. According to the NACA Standard Atmosphere, the most probable temperature at 42.6 km is about + 32°C, the probable absolute minimum -73°C.

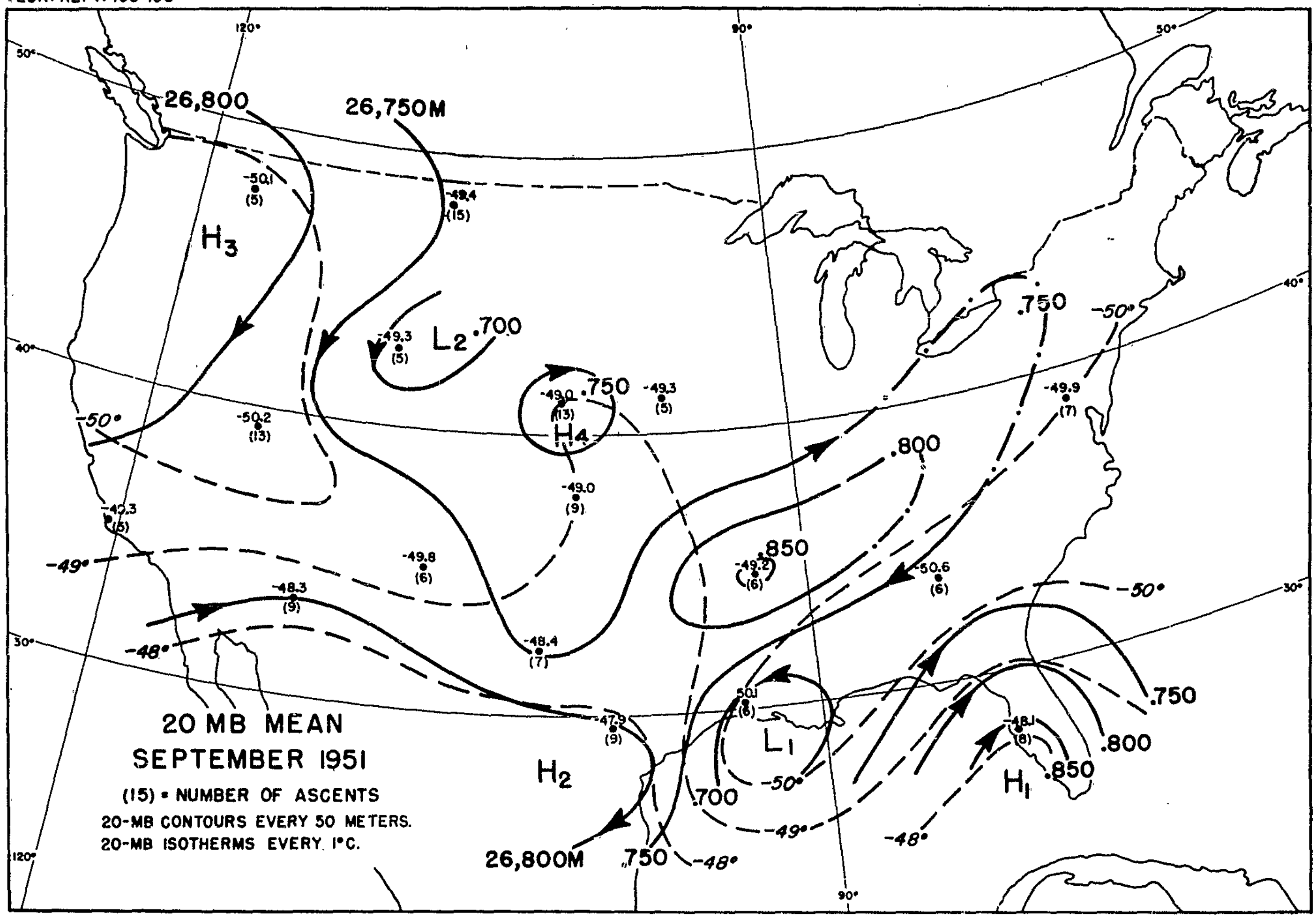
On the whole, there is no indication of temperatures approaching 0°C in 32-42km layer.

XIII CONCLUSIONS

Examination of 356 radiosonde soundings reaching from 15mb to 10mb, indicate the following facts.

1. On the average, the 10-mb temperatures are contained within -38°C to -52°C range.

2. Exceptional values of -5°C to -10°C were found in four cases at 10mb indicating that temperatures above 0°C may be, perhaps, reached very occasionally.



26,800
26,750M
H3
L2
.700
.750
H4
.800
.850
-50°
-49°
-48°
L1
H2
H1
.700
-50°
-49°
-48°
26,800M
.750
-48°
.750
.800
.850
-50°
20 MB MEAN
SEPTEMBER 1951
(15) = NUMBER OF ASCENTS
20-MB CONTOURS EVERY 50 METERS.
20-MB ISOTHERMS EVERY 1°C.

FIG. 8

3. The lapse rate in the 20.6-30.9 km layer is much smaller than usually indicated in the literature. The rate of warming with height decreases rapidly with increasing elevation.

4. In 16% of all cases, the 10-mb level lies in a region in which cooling with height occurs. This cooling may take place in the whole 100-10mb layer or in thinner layers such as 80-10mb, 50-10mb, 25-10mb, etc.

5. The average 24-hour temperature change at 10-mb is at least twice as great as that at 100mb. This change increases very regularly with height in the 100-10mb layer.

6. There is a marked seasonal variation of the mean and extreme temperatures at 10mb. The highest means and highest extremes occur in July.

7. On daily synoptic maps covering area from 9°N to 79°N, the extreme range of 100-mb temperatures was 36°C, and that on 10-mb map was 15°C.

8. In the mean maps, the range of 100-mb temperatures over U. S. A. and Central America was 41.6 C, that on the 10-mb map was only 2.7 C. A barotropic layer seems to be present from the Equator to the Pole in all months. This layer may lie anywhere between 60 and 10mb.

XIV. REFERENCES

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APPENDIX

ESTIMATE OF ERRORS IN COMPUTING HEIGHT OF PRESSURE SURFACES

The thickness of an isobaric layer is computed from

$$h = C \int_{p_2}^{p_1} T \, d \; (\ln p) \tag{1}$$

where $\underline{C}$ is a constant, $\underline{T}$ temperature (strictly speaking virtual temperature), $\underline{p_1}$ and $\underline{p_2}$ pressure at lower and upper boundary of the layer respectively.

Let us consider how an error in the temperature element, ΔT , and an error in the pressure element, Δp , will affect the thickness computation.

In the following primes indicate <u>reported</u> values, and unprimed quantities indicate <u>true</u> values.

Let $\underline{P'}$ be a point on the <u>reported</u> temperature curve A'B' plotted on an adiabatic diagram in figure 1.

The reported values at this point is $\underline{p'}$ and $\underline{T'}$. Because of the temperature error $\Delta \underline{T}$ the true temperature at the point of measurement is $T = T' - \Delta T$, and because of the pressure error Δp this is the true temperature not at pressure $\underline{p'}$ but at pressure $\underline{p} = \underline{p'} - \Delta p$. Thus the <u>reported</u> condition of the atmosphere at the geometrical point of measurement, represented by point $\underline{P'}$ in the adiabatic diagram, is generally different from the <u>true</u> conditions at the geometric point of measurement, as represented by point $\underline{P}$ in the adiabatic diagram.

If we know what $\Delta \underline{p}$ and ΔT were in the whole layer from $\underline{p_1}$ to $\underline{p_2}$, we could by this method construct the true sounding AB and compute the <u>true</u> thickness between $\underline{p_1}$ and $\underline{p}_2$ by means of (1).

As the errors are mostly unknown we cannot do this. However, we can calculate what errors the computed thicknesses may contain based on estimates of the instrumental errors.

In the integral in (1) above it is of course the true corresponding values of $\underline{p}$ and $\underline{T}$ that should appear. From figure 1 it is seen that the reported temperature $\underline{T''}$ at the true pressure $\underline{p}$ can be written

$$T'' = T' - \frac{\partial T'}{\partial p'} \Delta p = T + \Delta T - \frac{\partial T'}{\partial p'} \Delta p$$

The error in thickness we get by using the reported curve A'B' instead of the true curve AB is from this

$$\Delta h = h' - h = C\int_{p_2}^{p_1} T''d\,(\ln p) - C\int_{p_2}^{p_1} Td\,(\ln p)$$

$$\Delta h = C\int_{p_2}^{p_1} \left(\Delta T - \frac{\partial T'}{\partial p'}\Delta p\right)d(\ln p)$$

or

$$(2) \qquad \Delta h = C \ln \frac{p_1}{p_2}\ \overline{\left(\Delta T - \frac{\partial T'}{\partial p'}\Delta p\right)}$$

where the bar indicates that the quantity underneath it is to be averaged over logarithmic pressure. On the Skew <u>T</u>-log <u>p</u> diagram this is equivalent to averaging over a vertical distance.

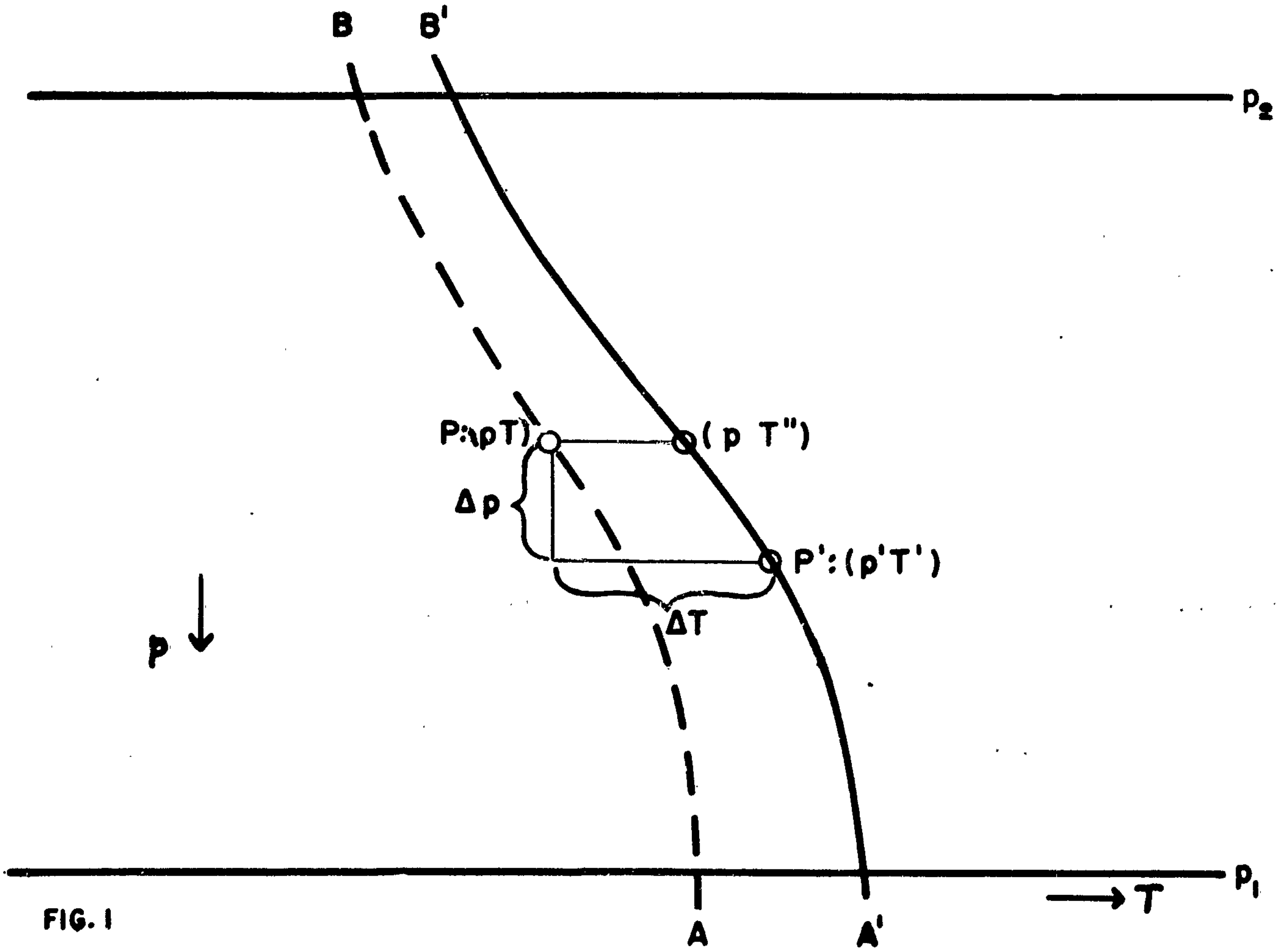

FIG. I

From (2) we see that the error in the computed thickness of an isobaric layer is made up of 2 components:

1. One component due to error in the temperature element:

(3) $$\Delta h_T = C \ln \frac{p_1}{p_2} \overline{\Delta T}$$

A reasonable estimate of the standard value of $\overline{\Delta T} = 1^{\circ}C$. This is supposed to be independent of the thickness of the layer and also of the elevation of the layer. Hence Δh_T is proportional to $\ln (p_1 / p_2)$ or roughly to the thickness of the layer. This leads to an error in the computed height of pressure surfaces that increases roughly in proportion with their height. The error at 100,000 feet (about 10 mb) is ten times that at 10,000 feet (700 mb). Since errors are mostly systematic (same sign all through the sounding) the error is cumulative.

2. One component due to error in the pressure element:

(4) $$\Delta h_p = -C \ln \frac{p_1}{p_2} \overline{\frac{\partial T'}{\partial p'} \Delta p}$$

We notice that this contribution to the thickness error depends on the lapse rate in the layer ($\partial T'/\partial p'$). In an isothermal atmosphere

$$\frac{\partial T'}{\partial p'} = 0 ,$$

$$\Delta h_p = 0$$

It might at first sight be concluded that since the stratosphere is supposed to be isothermal or nearly so, the error in the pressure element is not so important for thickness computations in the stratosphere. But this is not so. Even if the linear lapse rate $- (\partial T/ \partial z)$ is smaller in the stratosphere than in the troposphere, the baric lapse rate $(\partial T/ \partial p)$ attains much larger values in the stratosphere.

An estimate of the standard value of $\overline{(\partial T'/\partial p')\Delta p}$ for a layer is not straightforward. An approximation can be obtained by assuming Δp constant throughout the sounding. This assumption cannot be far off since the incremental error of the pressure element is much smaller than the absolute error. The development agency of the USAF radiosondes quotes standard values, for incremental error = 1 mb, for the absolute error 3 mb below 150 mb and 1.5 mb above 150 mb. It is, however, safer to assume a standard of value for the absolute error of 3 mb also above 150 mb. With this assumption we can write (4).

$$\Delta h_p = -C \ln \frac{p_1}{p_2} \overline{\frac{\partial T'}{\partial p'}} \Delta p \tag{5}$$

For an estimate of the standard value of Δh_p we will base it on an average sounding made up of 508 soundings from all seasons between 9°N and 65°N in the U.S. and Canada:

p =	1000	700	500	400	300	200	150	100	50	25	10	5 mb
T =	+15	+1	−14	−25	−40	−54	−59	−61.1	−56.5	−50.9	−45.0	−36.6 °C

In Table 1 below is computed the errors in thickness of the various isobaric layers from sea level to 5 mb based on this mean sounding. Listed in column 1 are values of $(\partial T'/\partial p')$ computed from this sounding. In column 2 we find the values of Δh_p assuming a constant error $\Delta p = +3$ mb. The numerical values of Δh_p in column 2 can be considered as standard values. In column 3 we find the values of $|\Delta h_T|$ assuming $|\overline{\Delta T}| = 1$°C. These can also be considered as standard values.

TABLE I.

Errors in computed thicknesses of various isobaric layers due to errors in the temperature and pressure data. Based on a mean sounding.

Isobaric layer	$\overline{\frac{\partial T'}{\partial p'}}$ °C/mb	Δh_p in feet Δp = constant = +3 mb	$\lvert\Delta h_T\rvert$ in feet $\lvert\Delta T\rvert$ = 1°C
1000/500	+0.06	−12	61
500/300	+0.13	−19	49
300/200	+0.14	−16	39
200/100	+0.07	−14	61
100/50	−0.09	+18	61
50/25	−0.24	+48	61
25/10	−0.39	+103	88
10/5	−1.68	+360	61

In Table II below the results in Table I are used to estimate the standard values of the error in the height of various pressure surfaces due to the two components. This can be done for the temperature component simply by adding the standard errors of the thicknesses below the pressure surface. This is done in column 2, Table II. It is assumed that the standard error of the height of the 1000mb surface is zero.

For the pressure component this cannot be done in the same way. Because $(\partial T/\partial p)$ changes sign from the troposphere to the stratosphere, and since we have assumed that the pressure error is more or less systematic (same sign throughout the sounding), errors accrued in the troposphere will be built off as we proceed up in the stratosphere. An estimate of the standard error in height of pressure surfaces due to error in the pressure element we can thus get by adding the algebraic values listed in column 2 in Table I and taking the numerical value of their sum. We then arrive at column 1 in Table II.

In column 3, Table II the combined effect of pressure and temperature error is obtained. Since pressure error and temperature error must be assumed to be independent and both normally distributed, the standard error in height is obtained from the formula

$$\Delta z = \sqrt{(\Delta z_T)^2 + (\Delta z_p)^2}$$

TABLE II.

Standard errors in computed heights of various pressure surfaces due to errors in the pressure and temperature data from the radiosonde. Based on a mean sounding.

Pressure surface	Δz_p in feet = Standard error in height due to a systematic error in pressure $\lvert\Delta p\rvert = 3$ mb	Δz_T in feet = Standard error in height due to a temperature error $\lvert\Delta T\rvert = 1°C$	$\Delta z = \sqrt{(\Delta z_p)^2 + (\Delta Z_T)^2}$ feet (rounded off)
1000	0	0	0
500	12	61	65
300	31	110	115
200	47	149	155
100	61	210	215
50	43	271	270
25	5	332	330
10	108	420	435
5	468	481	670

From Table I it is evident that while the error in the pressure element causes little trouble for the computation of thicknesses of isobaric layers in the troposphere, it becomes increasingly important in the stratosphere. In the 25/10-mb layer it has become the dominant error.

However, due to the reversal of lapse rate in the stratosphere, the effect of the pressure error in the computation of heights of pressure surfaces is not so bad. From Table II, column 1, it is seen that this compensation is most complete near the 25-mb level. From there on upwards Δz_p increases rapidly and is near 5 mb of the same magnitude as Δz_T.

From column 3, Table II, can be seen that the pressure element error hardly affects the standard error in the computed heights of pressure surfaces up to and including 10 mb. The temperature error is decisive. At 5 mb they become roughly of equal importance and above 5 mb Δz_p will soon predominate.

If we assume that it becomes impractical to draw maps of synoptic pressure surfaces with the present coverage of data when the standard error of the height reports is 400 feet or larger, the highest pressure surface we should attempt to map lies somewhere between 25 and 10 mb, about 15 mb. The 400 feet value may, if anything, to be too large.

It is concluded that mapping of the 10 mb surface with present quality of reports is not feasible on a synoptic basis.

This, however, does not prevent us from drawing climatological maps for higher levels, provided the sample of high reaching reports were large enough.

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